

Kim M. Cardosi

Research and
Special Programs
Administration
John A. Volpe National
Transportation Systems Center
Cambridge, MA 02142-1093

Final Report
June 1994

This document is available to the public
through the National Technical Information
Service, Springfield, VA 22161



U.S. Department of Transportation
Federal Aviation Administration

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

Kim M. Cardosi			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) John A. Volpe National Transportation Systems Center Research and Development Administration Transportation Systems Center Cambridge, MA 02142			8. PERFORMING ORGANIZATION REPORT NUMBER DOT-VNTSC-FAA-94-11
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Federal Aviation Administration Research and Development Service 800 Independence Ave., S.W. Washington, DC 20591			10. SPONSORING/MONITORING AGENCY REPORT NUMBER DOT/FAA/RD-94/15
11. SUPPLEMENTARY NOTES			
12a. DISTRIBUTION/AVAILABILITY STATEMENT This document is available to the public through the National Technical Information Service, Springfield, VA 22161			12b. DISTRIBUTION CODE
13. ABSTRACT (Maximum 200 words) The purposes of this analysis were to examine current pilot-controller communication practices in the terminal environment. Forty-nine hours of voice tapes from local positions in ten Air Traffic Control Towers (ATCTs) were examined. There were 8,444 controller-to-pilot messages (e.g., clearances to takeoff or land, instructions to hold short or change radio frequencies, etc.) examined in this study. The complexity of the controller's message (i.e., the number of pieces of information) was examined and the number of erroneous readbacks and pilot requests for repeats were analyzed as a function of message complexity. Pilot acknowledgements were also analyzed; the numbers of full and partial readbacks, and acknowledgements only (i.e., "roger") were tallied. Fewer than one percent of the messages resulted in communications errors. Among the error factors examined were: complexity of the message, type of acknowledgement, use of call sign in the acknowledgement, type of information in error, and whether or not the controller responded to the readback error. Instances in which the controller contacted the aircraft with one call sign and the pilot acknowledged the transmission with another call sign were also examined. The report concludes with recommendations to further reduce the probability of communication errors.			
14. SUBJECT TERMS Pilot-Controller Communications			15. NUMBER OF PAGES 28
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT

Science Applications International Corporation (SAIC). David Mallek of SAIC performed much of the data analysis and provided other technical support. We thank them and their supervisor, Bryan Brett, for their many hours of tedious analysis. Dr. Jordan Multer assisted in designing the test plan, provided critical comments in the initial stages of this work, and provided a great deal of administrative support to the project. Dr. Judith Burki-Cohen provided helpful comments on an earlier draft of this report. Finally, we thank the quality assurance specialists at the participating ATC facilities who supplied the tapes for this analysis.

AREA (APPROXIMATE)

1 square inch (sq in, in²) = 6.5 square centimeters (cm²)
 1 square foot (sq ft, ft²) = 0.09 square meter (m²)
 1 square yard (sq yd, yd²) = 0.8 square meter (m²)
 1 square mile (sq mi, mi²) = 2.6 square kilometers (km²)
 1 acre = 0.4 hectares (he) = 4,000 square meters (m²)

AREA (APPROXIMATE)

1 square centimeter (cm²) = 0.16 square inch (sq in, in²)
 1 square meter (m²) = 1.2 square yards (sq yd, yd²)
 1 square kilometer (km²) = 0.4 square mile (sq mi, mi²)
 1 hectare (he) = 10,000 square meters (m²) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
 1 pound (lb) = .45 kilogram (kg)
 1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
 1 kilogram (kg) = 2.2 pounds (lb)
 1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
 1 tablespoon (tbsp) = 15 milliliters (ml)
 1 fluid ounce (fl oz) = 30 milliliters (ml)
 1 cup (c) = 0.24 liter (l)
 1 pint (pt) = 0.47 liter (l)
 1 quart (qt) = 0.96 liter (l)
 1 gallon (gal) = 3.8 liters (l)
 1 cubic foot (cu ft, ft³) = 0.03 cubic meter (m³)
 1 cubic yard (cu yd, yd³) = 0.76 cubic meter (m³)

VOLUME (APPROXIMATE)

1 milliliters (ml) = 0.03 fluid ounce (fl oz)
 1 liter (l) = 2.1 pints (pt)
 1 liter (l) = 1.06 quarts (qt)
 1 liter (l) = 0.26 gallon (gal)
 1 cubic meter (m³) = 36 cubic feet (cu ft, ft³)
 1 cubic meter (m³) = 1.3 cubic yards (cu yd, yd³)

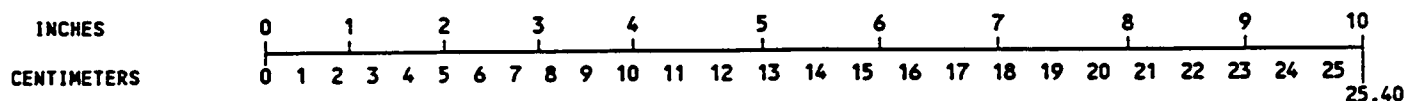
TEMPERATURE (EXACT)

$$[(x-32)(5/9)]^{\circ}\text{F} = y^{\circ}\text{C}$$

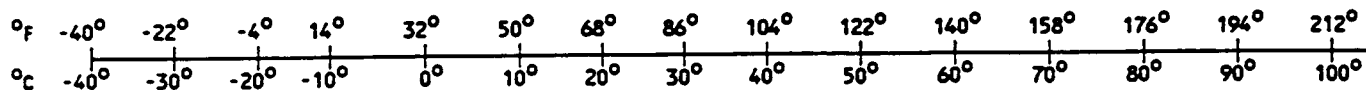
TEMPERATURE (EXACT)

$$[(9/5)y + 32]^{\circ}\text{C} = x^{\circ}\text{F}$$

QUICK INCH-CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION



For more exact and or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price \$2.50. SD Catalog No. C13 10286.

3.	ROUTINE COMMUNICATIONS PRACTICES	5
3.1	Message Complexity	5
3.2	Message Acknowledgement	6
3.2.1	Use of Call Signs in Readbacks	7
3.2.2	Message Complexity and Incidence of Readbacks	7
3.3	Miscommunications	9
3.3.1	Message Complexity and Readback Errors	9
3.3.2	Readback Errors and Type of Information	12
3.3.3	Hearback Errors	13
3.3.4	Message Complexity and Pilot Requests for Repeats	13
3.3.5	Call Sign Discrepancies	14
3.3.6	Coincident Factors	15
4.	CONCLUSIONS	17
	LIST OF ACRONYMS	19
	REFERENCES	20

LIST OF TABLES

<u>Table</u>	<u>Page</u>
3-1. Percentage of Controller Messages as a Function of Complexity	6
3-2. Pilot Responses to ATC Messages	6
3-3. Percentage of Readbacks and Readback Errors as a Function of Message Complexity	10
3-4. Distribution of Readback Errors by Type of Information .	12
3-5. Percentage of Transmissions Requiring Full or Partial Repeat Due to Pilot Request	14
3-6. Call Sign Discrepancies	15

necessary to correct the problem. Depending on the nature of the error, miscommunications have the potential of narrowing the margin of safety to an unacceptable level. Information obtained by sampling controller-pilot voice communications is useful in a variety of ways. Not only does it give insights into the frequency of occurrence of specific practices that are known to affect the efficiency of communications, but it also allows us to address specific questions that need to be answered to develop and evaluate new systems and procedures.

The purposes of this tape analysis were to examine current pilot-controller communication practices in the local control (tower) environment and to analyze the communication errors in detail. Forty-nine hours of voice tapes from ten Air Traffic Control Towers (ATCTs) were examined. There were 11,234 controller-to-pilot transmissions in this sample. This included 8,444 messages of substance (e.g., clearance to takeoff or land, instructions to hold short or change radio frequencies, etc.) and 2,790 requests for information, salutations, etc.

The majority of these controller messages contained one, two, or three pieces of information and were acknowledged with a full or partial readback. Less than one percent of the pilots' readbacks contained an error. There were only seven instances in which a controller did not notice the error in the pilot's readback. This represents 37% of the readback errors and less than one-tenth of one percent of the total number of controller messages.

The single most common type of readback error involved confusing the right and left runways of the same number. Such errors accounted for 21% of the 19 readback errors found in the analysis. An additional 32% of the readback errors were due to various types of errors associated with taxi instructions.

There were also 81 instances (.9% of the messages) in which the pilots responded to controller transmissions with different call signs than the controllers used. What was surprising about these incidents was that less than half of these call sign discrepancies were corrected.

There were 78 instances (less than 1% of the messages) of pilots requesting that a controller repeat all or part of the transmission. The rate of miscommunications (i.e., readback errors and pilot requests for repeats) for messages containing one to five pieces of information was less than 1% at each level

One of the most striking findings of this analysis was how few communication errors were found. A readback error rate of less than one percent is a tribute to the pilots and controllers operating in the National Airspace System. Still, pilots and controllers need to be aware that catching readback errors is a difficult task, particularly when combined with other duties that need to be performed simultaneously. Pilots need to be encouraged to ask for clarification, rather than expect the controller to catch readback errors. Pilots should also be diligent about using their full call signs to acknowledge controller transmissions. Controllers should listen for the call sign, as well as the content, of the pilot's readback. Controllers should also continue to warn pilots when there are similar call signs on the same frequency, whenever possible. Such practices and increased awareness can further reduce the probability of communication problems and further increase the margin of safety.

define the nature and causes of communication errors, much more work is needed. The sheer volume of Air Traffic Control (ATC) communications makes human error inevitable. The opportunity for miscommunications is constant and the consequences can range from annoying to dangerous. At the very least, miscommunications result in increased frequency congestion and increased controller workload, as more communications are necessary to correct the problem. Depending on the nature of the error, miscommunications have the potential of narrowing the margin of safety to an unacceptable level.

It is well-known that pilot-controller communications are not rigidly uniform. The exact format and wording of messages relayed by controllers and pilots vary as a complex function of the airspace environment, controller and pilot workload, and individual style. For example, while pilots are encouraged (in all but the busiest ATC environments) to readback key information (e.g., altitude) as a matter of good communication practice, it is not uncommon for pilots to acknowledge a transmission with the reply "roger" or "good day", instead of a readback of even part of the controller's message. While this practice deprives the controller of the opportunity to catch a readback error, it is often necessary on congested frequencies during extremely busy traffic periods. Exactly how often this occurs had not yet been studied in the terminal environment, nor was it known how often these practices contribute to communication errors. Similarly, it is common for a pilot to request the controller to repeat a message ("say again"). However, the percentage of all transmissions that need to be repeated had never been examined for tower communications. This additional transaction adds to a controller's workload and to frequency congestion. Information obtained by sampling pilot-controller voice communications is useful in a variety of ways. Not only does it give insights into the frequency of occurrence of specific practices that are known to affect the efficiency of communications, but it also allows us to address specific questions that need to be answered to develop and evaluate new software and procedures. For example, knowing the percentage of clearances that need to be repeated by controllers would be useful in the evaluation of the efficiency of sending ATC messages via data-link.

Previous work in ATC voice tape analysis has focussed on TRACON and on en route communications. Morrow, Lee, and Rodvold (1993), examined TRACON communications and found a readback error rate of less than one percent with only half of these errors "repaired"

clearances containing one to four pieces of information and a 8% rate for transmissions containing five or more elements. Although clearances containing five or more pieces of information constituted only 4% of the messages examined, it accounted for 26% of the readback errors found in the sample.

The purpose of this tape analysis were to examine current pilot-controller communication practices in the local control (tower) environment and to analyze the communication errors in detail. While the current analysis focussed on the tower local control position, future analyses will examine pilot-controller communications with ground control and TRACON positions. These analyses document the incidence (i.e., on what percentage of the communications is this noted?) and consequences of the following practices:

- pilots acknowledging controller transmissions with complete readbacks;
- pilots acknowledging controller transmissions with incomplete readbacks;
- pilots responding to controller transmissions with only an acknowledgement (i.e., "roger");
- requests for repeat of controller transmissions;
- controllers failing to detect pilot readback errors; and
- controllers relaying multiple instructions in a single transmission.

An analysis of ASRS reports is currently being conducted to provide a larger data base suitable for an in-depth study of miscommunications that is not practical with tape analysis, alone. While the tape analysis can address the frequency with which miscommunications occur, it cannot provide a suitable data base for extensive errors analysis, since the frequency of errors is small relative to the total number of transmissions.

These facilities were selected to sample different geographical locations (i.e., east coast, west coast, central), different workload levels, and different traffic mixes (e.g., inclusion of towers with a relatively high proportion of foreign carriers). Twenty-four hours of tape analyzed were from periods of high workload (as defined by the facility) and 24 hours were from periods of moderate workload. Towers with more than one local position (e.g., departure and arrival) were asked to sample the different positions. The purpose of these selections was to achieve a representative sample of different local operations (excluding the very low workload periods, e.g., middle of the night, which would yield little interesting data).

The tapes were analyzed by three subject matter experts (one former controller and two pilots). All communication errors were transcribed and set aside for separate analysis.

Part of the analysis examined miscommunications. This included communication errors and pilots' requests for repeat of part or all of the transmission. Miscommunications were examined as a function of the complexity of the controller's message. Message complexity was measured in terms of the number of separate elements contained in a single transmission. Each word, or set of words, the controller said that contained a new piece of information to the pilot, and was critical to the understanding of the message, was considered to be an element. An element could also be considered as an opportunity for error. For example, "American 123, cleared to land runway two niner" was considered two elements. However, "American 123 cleared to land runway two niner left" was counted as three elements, since there is an opportunity to mistakenly land on two niner right. Usually, the counting is straightforward. Changes in altitude or heading are each considered to be one element as are individual taxiways, runway numbers, and left, right. Landing and taxi instructions can contain many elements. Controller transmissions containing clearances to takeoff or land can also include traffic and wind advisories, and taxi instructions. Taxi instructions, even the limited instructions that would be issued on a busy local control frequency can be surprisingly complex. For example, "Taxi down the runway, turn left at Dixie, join November and taxi all the way down to Tango. Hold short of Runway two

¹ The tapes from each facility were from non-consecutive hours in single hour increments.

memory load were counted as an element, since it serves only to attract the pilot's attention and is not something that must be remembered as a part of the message. It should be noted that any such counting scheme is necessarily arbitrary. Whether a radio frequency such as "123.45" should be counted as a single element or as four elements (since the one is invariant) is debatable. It is not reasonable to assume that all elements impose the same memory load. It is probably easier to remember to cross a specific taxiway than it is to remember an unfamiliar radio frequency. Yet, for counting purposes, each would be considered as one element. The error analysis does, however, examine errors with respect to the type of information transmitted.

acknowledgements, etc., and were tallied, but not included in the analysis.

3.1 MESSAGE COMPLEXITY

The length and complexity of messages issued by controllers in a single transmission is often informally cited by pilots as a great source of frustration and potential errors. Indeed, a study of en route communications showed that most of the readback errors involved lengthy controller transmissions (i.e., those that contained more than four pieces of information). Also, Morrow, Lee, and Rodvold (1993) found that incorrect readbacks were more frequent for TRACON communications containing two or more pieces of information than those containing only one. In a part-task simulation study, Morrow (personal communication) found that incorrect readbacks and requests for clarification were more frequent after long messages (i.e., those containing four pieces of information) than for shorter messages.

Table 3-1 shows the distribution of messages by complexity level. The majority of messages contained one, two, or three pieces of information. Twenty percent of the messages contained one element (e.g., cleared for take-off) and 38% of the messages contained two elements (e.g., position and hold on runway two six). Sixteen percent of the messages contained three elements (e.g., position and hold runway two six right) and almost half (46%) of the messages contained four or more elements. It is important to realize that, in this environment, controllers need to convey a certain amount of information in a single transmission. Consequently, even the simplest of instructions can have three or more elements. For example, "USAir 123, position and hold runway two two left, departing traffic runway one four" has five elements.

3	16%
4	15%
5	14%
6	7%
7	5%
8	3%
9 or more	2%

3.2 MESSAGE ACKNOWLEDGEMENT

As Table 3-2 shows, the majority of the 8,444 messages were acknowledged with a full or partial readback. Twenty-eight percent of the messages were acknowledged with a full readback and 37% were acknowledged with a partial readback. Twenty-seven percent of the messages were directly acknowledged without a readback (e.g., with a "roger"), while seven percent were acknowledged with only a mike click. Less than one-half of one percent were acknowledged indirectly (e.g., with a question, or a request for a different clearance or additional information) or not acknowledged at all.

TABLE 3-2. PILOT RESPONSES TO ATC MESSAGES

Full Readbacks	28%
Partial Readbacks	37%
Acknowledgement Only	27%
Mike Clicks	7%
No Acknowledgement	<1%
Total	100%

Less than one percent of the readbacks contained an error. This error rate refers to instances in which the pilot read back

aircraft) in response to 77% of the messages issued and in 61% of the readbacks containing an error. A partial call sign (e.g., airline name alone or flight number alone) was given in an additional 11% of the readbacks. No call sign was given in 28% of these readback errors. Of the erroneous readbacks given without call signs or with only a partial call sign, 57% were from Part 121 or Part 135 air carriers.

The potential hazards inherent in responding with an incomplete call sign are apparent in the following example. The controller instructs AirCarrier A 1471 to contact departure. In fact, the controller intended to instruct AirCarrier B 1471 to contact departure. The pilot responded to this instruction with "1471, good day". In this instance, there was no other aircraft on the frequency with the call sign of AirCarrier A 1471 and the controller had been communicating with the pilot he intended to contact, so he was easily able to recognize his voice. Still, in the era of hubs (where many aircraft from the same company are operating simultaneously) and similar call signs (such as aircraft from different companies having the same or similar flight numbers), pilots need to be particularly diligent about using their complete call sign.

3.2.2 Message Complexity and Incidence of Readbacks

The longer the controller's transmission, the more likely the pilot was to respond with a full or partial readback, rather than just an acknowledgement. Figure 3-1 shows the percentage of readbacks as a function of message complexity. Controller transmissions that contained one or two pieces of information, such as "Contact ground" or "Fly heading two one zero, contact departure," respectively, were most likely to be responded to with only an acknowledgement. Approximately one-half of the transmissions containing three pieces of information were acknowledged with a readback, and 75% of the longer transmissions were acknowledged with a full or partial readback. (Recall that partial readbacks were more common than full readbacks.) Since taxi instructions are usually complex and contain critical details that can make the difference between an uneventful taxi and a runway incursion, it is prudent that pilots respond with at least a partial readback.

It should be noted that each partial or missing readback presents an opportunity for a communications error, since it does not

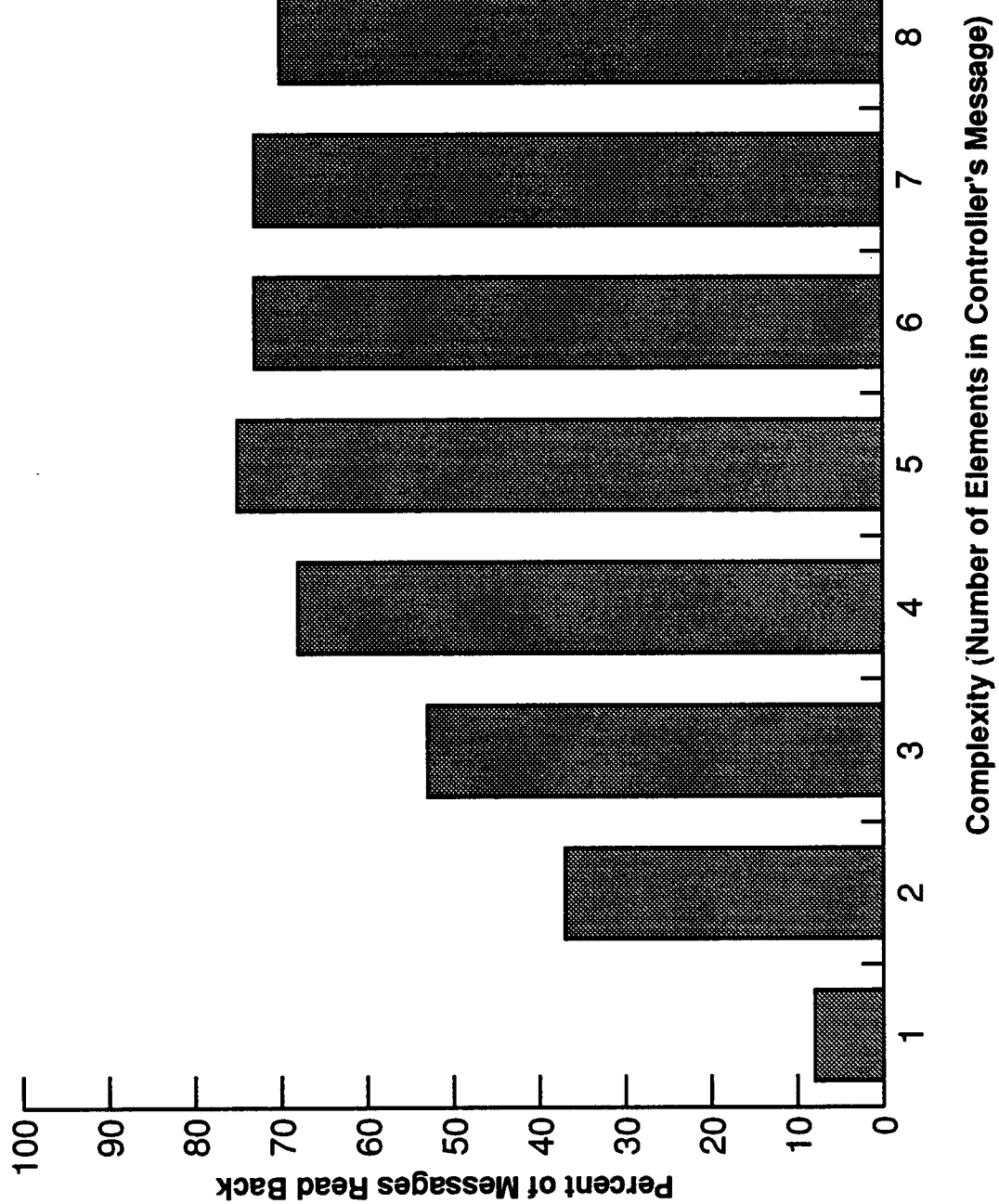


FIGURE 3-1. PERCENT OF MESSAGES READ BACK AS A FUNCTION OF MESSAGE

For the purposes of this study, miscommunications consisted of readback errors and pilots' requests for a repeat of all or part of the controller's transmission. Many factors can contribute to miscommunications. One important factor that can lead to both readback errors and to hearback errors is expectation. As humans, we are predisposed to hear what we expect to hear. Voice tape analysis is not a good vehicle for studying the effects of expectation on communication errors. However, the effects of expectation can be quite apparent in some of the errors noted. For example, expectation can lead to readback errors, when what is expected is not what is transmitted. For example, "Maintain minimum approach speed, (pause) change runway, one six left, cleared to land" was read back as, "OK, minimum approach speed, uh, cleared to land one six right". Note how the expectation to land on one six right was stronger than the "change runway" issued by the controller. It is important to note that, in this instance, the controller did not stress this part of the transmission with a change of voice inflection. There was, however, a significant pause before, and a slight pause after, "change runway".

There are many other important factors that can contribute to miscommunications that cannot be identified in a tape analysis. These factors include pilot and controller workload and distractions. It is useful, however, to examine the important factors that can be studied, such as complexity of controller transmission and type of information in error.

3.3.1 Message Complexity and Readback Errors

Logically, the more information contained in a single transmission, the higher the probability of an error. The more elements in a message, the higher the memory load imposed upon the pilot. There were only 19 communication errors found in the 48 hours of tape analyzed. This represents less than one-fifth of one percent of the 8,444 messages issued. Table 3-3 shows the percent of pilot readbacks and readback errors as a function of the complexity of the controller's original message. Column 1 shows the complexity level of the message, that is, the number of pieces of information contained in the transmission. Column 2 shows the percentage of these transmissions that were responded to with a full or partial readback (as opposed to an acknowledgement only). This was computed by dividing the number of pilot readbacks at that level by the number of controller

Messages containing eight pieces of information had a readback error rate of almost two percent. Still, there is no reason to suspect that there is anything unusual about messages with eight pieces of information.

TABLE 3-3. PERCENTAGE OF READBACKS AND READBACK ERRORS
AS A FUNCTION OF MESSAGE COMPLEXITY

Complexity Level	Percentage of Full and Partial Readbacks	Number of Readback Errors	Percentage of Readback Errors
1	8%	0	0%
2	37%	2	.3%
3	53%	1	.1%
4	68%	4	.4%
5	75%	4	.3%
6	73%	1	.2%
7	73%	3	.8%
8	70%	4	1.8%
9 or more	80%	0	0%

The complexity of the controller's transmission seems to have had little effect on the readback error rate in these communications. This finding stands in sharp contrast to the results of a study of the en route environment. An analysis of voice tapes from Air Route Traffic Control Centers (ARTCCs) showed that the readback error rate increased significantly with the complexity of the controller's transmission (Cardosi, 1993). However, for several reasons, the number of pieces of information in the local transmissions studied cannot predict the pilot's memory load imposed by the transmission as well as it does in the en route environment. First, many of the lengthy transmissions in a terminal environment are predictable, based on standard procedures (e.g., SIDs and STARs) and the information available on the ATIS and via the partyline (i.e., transmissions between

readback or execution of those instructions, even though the transmission may be lengthy, than a pilot who receives a lengthy and unexpected transmission.² Third, this analysis, by default, counted each piece of information (e.g., each taxiway) as equal and independent. In reality, many of these pieces of information could be logically grouped by the pilot and would not impose the same memory load as the same number of unrelated pieces of information. Unfortunately, the actual memory load imposed by a given transmission cannot be evaluated in such a tape analysis, since it depends on factors such as pilot expectations, the pilot's familiarity with the airport, and readiness to write down a clearance.

Support for the fact that something other than the complexity of the controller's transmission is contributing to the readback errors, comes from the lack of readback errors for transmissions that contained nine or more elements. Recall that 80% of these transmissions were responded to with a full or partial readback. It is unlikely that these transmissions came as a surprise to the pilot and, by chance, did not lead to any readback errors. It is more likely that the pilots were prepared, in one way or another, for these lengthy transmissions. It is important to note that transmissions where the controller warned the pilot of its length (as in asking if the pilot was "ready to copy") were not analyzed separately, nor were they excluded from the error analysis.³

² As previously noted, however, expectation is a double-edged sword. Knowing what message to expect can help the pilot to hear and remember the message as long as the expected message is what was transmitted.

³ The number of readback errors was so small that excluding the small number of lengthy, but "prompted" transmissions would have had little effect on the error rate.

readback errors found in the analysis, and errors involving altitude accounted for 16% of the errors.

TABLE 3-4. DISTRIBUTION OF READBACK ERRORS BY TYPE OF INFORMATION

Type of Information in Readback Error	Number of Readback Errors	Proportion of Readback Errors
Taxi Instructions	7	37%
Right and Left of Same Runway Number	5	26%
Altitude	3	16%
Heading	2	10%
Transponder Code	1	5%
Other	1	5%

A common type of error involves transposing numbers in a message. In the following example, the pilot confused the numbers in the runway with the heading. "Turn right, heading **one three five**, Runway **one two**, cleared for takeoff, traffic arriving niner right will hold short of the intersection" was read back as, "Cleared for takeoff, heading **one two zero**". The controller missed this particular readback error and later had to correct the pilot's course. In this instance, the unconventional sequence of instructions and information (i.e., heading, runway number and cleared for take-off, rather than cleared for take off, runway number and heading) may also have contributed to the readback and hearback errors.

In addition to these readback errors, there was one instance of the wrong aircraft accepting a clearance to land intended for another aircraft. Contributing to this error (both on the pilot's and controller's part) were the physical proximity of the two aircraft and the similar call signs. Both aircraft were on

⁴ In addition to the readback errors shown in this table, there was another readback error that went unchallenged by the controller. In this instance, an aircraft was instructed to cross Runway 29 Left. The pilot read back that he would cross Runway 29 Right. Since this aircraft had landed on 29 Right (the very runway he was proposing to cross), this error was regarded as a "misspeak" and was not tallied as a readback or a hearback error.

3.3.3 Hearback Errors

There were only seven instances in which the controllers did not notice an error in the pilot's readback. This represented 37% of the 19 readback errors and less than one-tenth of one percent of the total number of messages. Most of these hearback errors followed readback errors of taxi instructions. Recall that the communications analyzed in this study were from local control positions and not ground control. These hearback errors did not occur while the controller was performing dual duties, since the tapes were from moderate and high workload periods and times in which these positions were not likely to be combined. In fact, three of the seven controller transmissions that resulted in a hearback error conclude with the instruction to contact the ground control frequency. However, since the number of errors is so small, and since the exact circumstances of the errors (such as the controller's duties at the time of the error) are unknown, a detailed analysis of these hearback errors is not possible. As with the previous study of en route communication, there were too few readback and hearback errors found in this study to contribute to our understanding of hearback errors.

3.3.4 Message Complexity and Pilot Requests for Repeats

Pilots who are unsure of all or part of their clearance should request a repeat of the part in question. Some pilots will readback *what they thought they heard* with the hopes that they are correct and, if not, then the controller will catch their error. In this sense, every "say again" and request for a repeat of part of the transmission is a readback and hearback error averted. Still, such requests, while necessary, add to the controller's workload as additional transmissions are needed to correct the problem. There were 78 instances (less than 1% of the messages) of pilots requesting that a controller repeat all or part of the transmission. Table 3-5 shows the percentage of messages followed by a pilot's request to repeat all or part of the transmission. The results are similar to those for pilot readback errors. Generally, the rate of pilot requests for repeats increases as message complexity increases, but never exceeds 2%, even for the most complex transmissions.

3.3.5 Call Sign Discrepancies

There were 81 instances (approximately one percent of the messages) in which a pilot responded to a transmission with a call sign that was different than the one used by the controller. In only one of these instances was there evidence that the other call sign was actually another aircraft on the same frequency. (This instance, in which one aircraft accepted a clearance to land intended for another aircraft, was described under the section on readback errors.) Table 3-6 shows the distribution of these call sign discrepancies. Twenty-eight percent of these transmissions contained clearances to land or takeoff, and 20% of these transmissions contained instructions to change frequencies. What was most surprising about all of these incidents was that only 48% of these call sign discrepancies were corrected. Only 26% of the call sign discrepancies that were corrected were done so with direct pilot questions or statements (e.g., "Was that for Airline 123?"), another three percent were corrected by direct controller questions or statements. The rest of the discrepancies were indirectly corrected by either the pilot or controller changing the call sign on a subsequent transmission to conform to what the other party used. In the majority (87%) of the call sign discrepancies that were corrected in this way, the controller changed the call sign used to conform to what the pilot had used. Approximately one-half (52%) of the all of call sign discrepancies went uncorrected as the controller continued to call the aircraft with one call sign and the pilot responded to the transmission with another.

(47%)	6%	6%	2.5%	1%	5%	2.5%	6%	9%	9%
Uncorrected (53%)	6%	10%	10%	1%	5%	2.5%	5%	6%	7%

In most cases, such call sign discrepancies do not result in any ill effects, or even ambiguity, since there are other cues that controllers can use to identify aircraft. In addition to the visual information that the controllers have in front of them on the flight (e.g., as to the location of the aircraft), they also have the pilot's voice. Without a call sign, the pilot's voice and the content and context of the message are the only cues that the controller has that he/she is still talking to the same aircraft. While this obviously presents an opportunity for error, it should be noted that none of these instances resulted in a problem. It should also be noted that transmissions of some clearances via datalink would eliminate many of these call sign confusions, but would not eliminate accidentally transmitting an instruction intended for another aircraft.

3.3.6 Coincident Factors

Pilots and controllers often informally discuss factors that they believe contribute to communication errors. In addition to message length, pilots often cite high pilot workload, fast controller speech rate and similar sounding aircraft call signs as contributing factors to communications problems. Controllers often cite controller workload, foreign pilots, similar call signs, and blocked transmissions as contributing factors. Voice tape analysis is not an appropriate method of examining pilot and controller workload or cockpit and controller distractions. However, it can offer a glimpse into the other factors. The following factors were examined as possible coincident events:

- similar sounding call signs on the same frequency;
- significant weather conditions;
- communications equipment malfunction;
- blocked transmissions;
- pilot's or controller's use of nonstandard phraseology;
- pilot's or controller's fast rate of speech; and
- pilot's or controller's accent.

signs were coincident with 12% of the miscommunications (but contributed significantly to only one communications error). Bad weather was coincident with 5% of the miscommunications and equipment malfunctions were coincident with 2%. Blocked transmissions, pilot's or controller's use of nonstandard phraseology, rate of speech, and accent, were not noted as coincident with any of the miscommunications.

It should be noted that the lack of significant results found in this portion of the analysis should not be interpreted as proof that none of the factors examined constitutes an ATC communications problem. First, the small sample of errors that was found in this study does not allow for an adequate examination of any single one of these factors. In order to examine the impact of any one of these factors on communications, the number of total incidence would need to be compared to the number of occasions in which it was found to contribute to a communications problem. For example, in order to study the similar call sign problem, the number of instances in which similar sounding call signs were on the same frequency would be compared to the number of instances in which this resulted in a communications problem. Such a series of studies was beyond the scope of this analysis. Also, the fact that a specific problem was not observed during the course of this study or the fact that a specific problem is not a common occurrence, does not lessen the severity of the consequences when it does occur. For example, there were no incidents of blocked transmissions that resulted in a communication error in the 48 hours of tape examined. Still, the consequences of a stuck microphone in busy airspace can be very serious. The fact that none of the factors examined were found to have significant effects is not meant to suggest that problems do not exist, nor should it preclude further study.

compound the problem of the inevitability of human error. It is not possible to reduce the number of communication errors by telling pilots and controllers to "pay attention". However, this analysis suggests that simple changes in current practices could reduce the risk of communication errors. Controllers should be encouraged to keep their transmissions brief and to look for readback errors. Perhaps, erroneous readbacks should be included in the traffic scenarios used in controller training, as a recent ASRS reporter suggests (ASRS Callback, 1992).

It is not realistic to expect air traffic controllers to catch all readback errors while performing their other duties. We are all set up to hear what we expect to hear. While controllers are not exempt from this law of human nature, we require a higher standard of information processing from them. Pilots and controllers need to be aware that catching readback errors is a difficult task, particularly when combined with other duties that need to be performed simultaneously. Often, during a pilot's readback, the controller's attention may already be on the next message that must be issued. This is particularly likely during high workload periods. Pilots need to be encouraged to ask for clarification, rather than expect the controller to catch readback errors. Pilots should also be diligent about using full call signs to acknowledge controller transmissions and to question call sign discrepancies (as in "... Was that for Air Carrier 123?"). Controllers should listen for the call sign, as well as the content, of the pilot's readback. Controllers should also continue to warn pilots when there are similar call signs on the same frequency, whenever possible. Unfortunately, it is not easy to define what constitutes "similar call signs". A list of potentially confusable call signs would be too lengthy to be useful. Clearly, call signs with different airline names, but the same flight numbers are similar, as are same airline flight numbers that differ only by one digit, or one syllable, as in the case of "two" and "ten". Such practices and increased awareness can further reduce the probability of communication problems and further increase the margin of safety.

ATCT - Air Traffic Control Tower

ATIS - Automated Terminal Information Service

SID - Standard Instrument Departure

STAR - Standard Terminal Arrival Route

TRACON - Terminal Radar Approach Control

Morrow, D., Lee, A., & Rodvold, M. 1993. Analysis of problems in routine controller-pilot communication. *International Journal of Aviation Psychology*, 3(4), 285-302.



2-2.	PILOT ESTIMATES OF PERCENTAGE OF APPROACH TIME SPENT MONITORING THE CD AND DG FOR THE SIX LEVELS OF CDI SENSITIVITY.....	2-11
2-3.	PILOT ESTIMATES OF WORKLOAD OBTAINED IN THE THREE APPROACH WINDOWS FOR THE SIX LEVELS OF CDI SENSITIVITY.....	2-11
2-4.	SAFETY PILOT ESTIMATES OF PILOT EFFORT DURING THE APPROACH FOR SIX LEVELS OF CDI SENSITIVITY.....	2-13
2-5.	INFLUENCE OF WINDOW AND CDI SENSITIVITY ON FLIGHT SMOOTHNESS.....	2-16
2-6.	PARTIAL CORRELATION OF FLIGHT QUALITY MEASURES WITH PILOT EFFORT AND PILOT WORKLOAD ESTIMATES.....	2-17

from 15,190 feet (2.5 nautical miles) to 475 feet (0.08 nautical miles) for a full-scale deflection. Increases in sensitivity of this magnitude decreased crosstrack Root Mean Square (RMS) error from an average of 0.22 to 0.04 nautical miles. Magnitude of the error and the influence of sensitivity on that magnitude were affected by distance from the missed approach point. Pilots reported that increases in sensitivity increased their workload and changed their distribution of attention among the aircraft instruments used for navigation and directional control.

well as the depth, width, and horizontal dimensions of the involved airspace that must be guaranteed obstruction-free. The width of the path that must be cleared is determined by measuring sources of navigation system error. One of these is "Flight Technical Error" (FTE) or "crosstrack error," which refers to the accuracy with which the pilot controls the aircraft. This is measured by the discrepancy between the indicated command on the display and the actual aircraft position. The smaller the FTE, the narrower the path width that must be clear of obstruction.

The display often used to indicate the aircraft's position relative to the desired track is called the course deviation indicator (CDI). The principal objective of this study was to determine the influence of CDI sensitivity on FTE (an increase in CDI sensitivity results in greater deflections of the CDI needle for a given displacement of the aircraft from the desired track). Other study objectives included determining the influence of CDI sensitivity on pilot workload and aircraft handling.

1.2 METHODOLOGY

Data on flight performance was collected from twelve instrument-rated pilots who flew nonprecision instrument approaches at six different levels of CDI sensitivity into a local, uncontrolled airport. The approaches were flown in an instrumented Piper Archer airplane, equipped with a LORAN-C receiver. Each pilot flew all approaches wearing a hood and provided estimates of pilot workload during each approach. Safety pilots provided estimates of pilot effort.

The remainder of this section describes the characteristics of the pilots, the aircraft and instrumentation used, and the study procedures.

1.2.1 Pilot Characteristics

The twelve pilots who participated in this study were volunteers who responded to a sign-up sheet posted at the Minute Man Airfield in Stow, Massachusetts. They normally flew out of Minute Man and were familiar with the Piper Archer airplane. All

1.2.2 Aircraft and Instrumentation

All data collection flights were made in a Piper Archer. This light, single-engine airplane with a fixed gear was selected due to its simplicity and because it is familiar to many pilots.

In addition to being fully IFR-equipped, the airplane contained a Northstar M1 LORAN-C receiver and a second set of airplane instruments. The LORAN-C and the duplicate aircraft instruments were connected to a minicomputer used for data recording in flight.

The M1 LORAN-C receiver is a standard, commercially available unit that was modified for this experiment by Northstar so that the following CDI sensitivities could be selected in flight for any approach:

- o 1/64 nautical miles (nm) per dot and 475 feet full scale, which is equivalent to Instrument Landing System (ILS) at middle marker
- o 1/32 nm per dot and 950 ft. full scale
- o 1/16 nm per dot and 1,900 ft. full scale
- o 1/8 nm per dot and 3,800 ft. full scale
- o 1/4 nm per dot and 7,600 ft. full scale
- o 1/2 nm per dot and 15,190 ft. (2.5 nm) full scale

Information output from the LORAN-C included ground speed, distance to the next waypoint, the name of the next waypoint, and crosstrack error.

The second set of instruments, including directional gyro, attitude indicator, altimeter, and turn-and-slip indicator, were mounted together with a vacuum pump in a 12-inch square aluminum box located behind the pilot's seat.

during the approach. Both estimates were made on a seven-point scale, with "seven" indicating very high workload or effort.

1.2.4 Setup

Each pilot flew all approaches wearing a hood and, when cued, estimated his workload. A safety pilot operated the LORAN, monitored the safety of the flight, and provided estimates of pilot effort after each approach. A technician (also called the "experimenter"), in the rear of the airplane, operated the data recording equipment and cued the pilot three times during the approach for workload estimates.

The twelve instrument-rated pilots were divided into two groups. Six of these pilots constituted a high flying-time group (100 hours or above); the other six constituted a low flying-time group (below 100 hours). These flying times were based on total instrument time.

Within each group, the six men were further divided into groups of three:

	<u>Number of pilots</u> (high)	<u>Number of pilots</u> (low)
Group A	3	3
Group B	3	3

Groups A and B refer to CDI sensitivity levels as follows:

Group A	1/2 nm per dot 1/8 nm per dot 1/32 nm per dot
Group B	1/4 nm per dot 1/16 nm per dot 1/64 nm per dot

in which he got the three sensitivity conditions was the same on each day.

The first approach of the day was always a practice approach at 1/4 nautical mile per dot. This value was selected because it is a common standard setting used with LORAN systems for operations within terminal areas. Data was recorded during the next six approaches. The pilot made two consecutive approaches at each of the three sensitivity levels assigned to him, in the assigned test order. The seven approaches took about two hours.

1.2.5 Procedure

Before each day's flight, the pilot was verbally briefed and given written material that described the test procedures. He was further provided with the appropriate sectional chart and approach plate (Figures 1-1, 1-2, and 1-3). The pilot was encouraged to make notes on the plate if desired. In addition, he was told how the seven-point workload scale was to be used:

- o A "1" on the scale represented very low workload. It indicated that all phases of the approach could easily be accomplished and that there was time to spare to attend to other aspects of the flight.
- o A "7" on the scale represented very high workload. It indicated that there was insufficient time to attend to all of the approach procedures and that no time could be spared for planning, or for unanticipated events.

The pilot was also given a description of how the LORAN-C operated, so that the automatic waypoint sequencing in the LORAN-C's flight plan mode was understood. Finally, the volunteer was reminded of the importance of keeping the CDI needle as close to the center as possible while flying the approach procedure, especially at the course intercept.

All test flights were flown between Minute Man Airfield in Stow and the Gardner Municipal Airport in Gardner, a distance of about 25 miles (Figure 1-1). The flight from Stow to Gardner and the seven approaches took more than two hours of continuous flying.

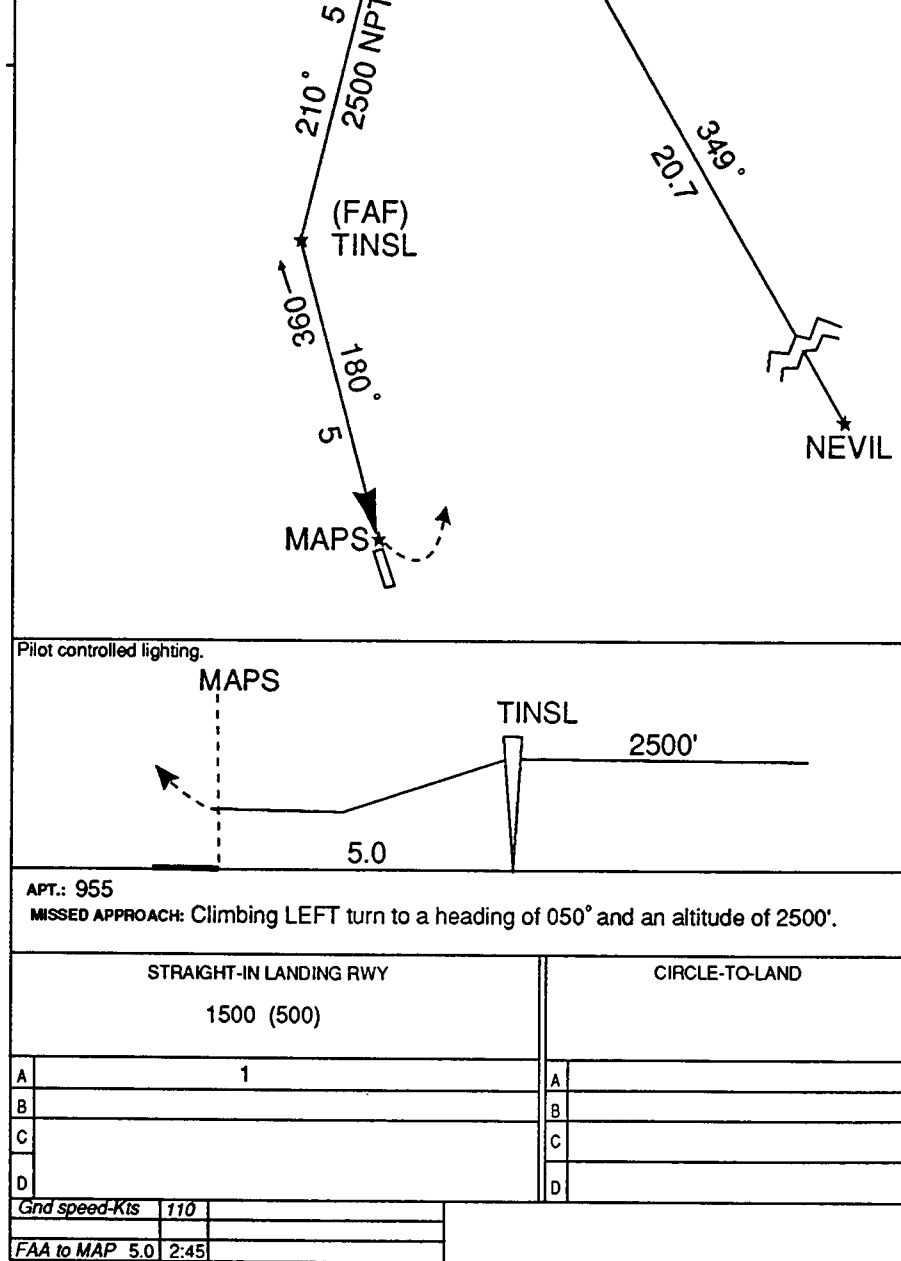


FIGURE 1-2. INSTRUMENT PROCEDURE CHART FOR RUNWAY 18 APPROACHES

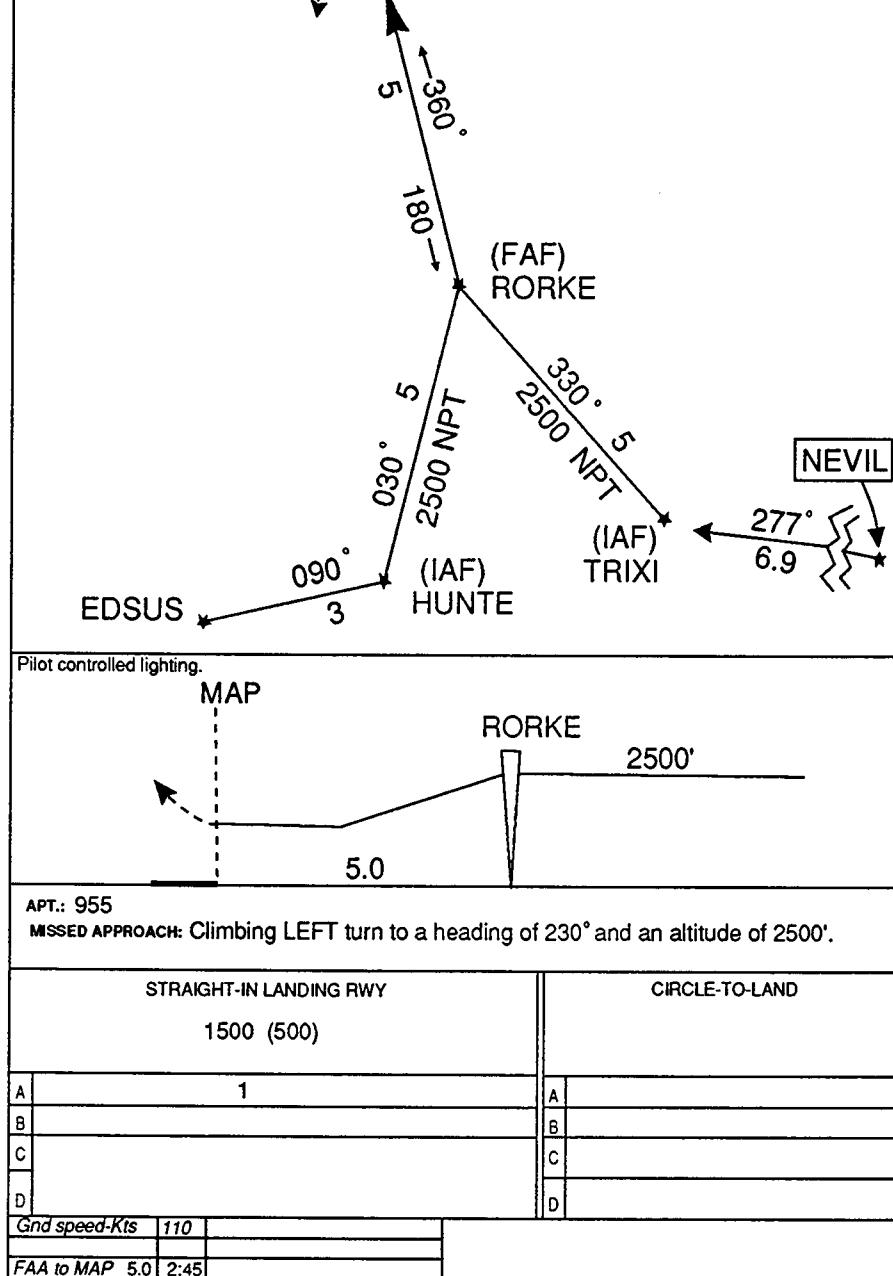


FIGURE 1-3. INSTRUMENT PROCEDURE CHART FOR RUNWAY 36 APPROACHES

safety pilot instructed the pilot to execute the missed approach procedure and to return to INNES (EDSUS) for another approach. The flight from the missed approach point to INNES or EDSUS could be flown without the hood if the pilot wished.

The pilot was required to maintain an air speed of 110 knots during the entire approach and an altitude of 2,500 feet until the final approach fix. He could then descend to 1,500 feet as indicated on the approach plate.

The pilot decided when to initiate each turn by referencing the distance-to-waypoint readout on the LORAN-C. He was asked to perform standard procedures at specific points in the approach to maintain workload at a realistic level, and to duplicate the activities required during an actual instrument approach at an uncontrolled airport, including:

- o Monitoring the Automated Terminal Information Service (ATIS) frequency of a nearby airport at the Initial Approach Fix (IAF) to obtain the altimeter setting.
- o Calling the Common Traffic Advisory Frequency (CTAF) to notify area traffic of the approach at one and two minutes inbound from the Final Approach Fix (FAF).

The pilot was debriefed at Minute Man Airport after the seven approaches had been completed. Debriefing discussions included obtaining:

- o The pilot's perception of CDI sensitivity's influence on workload.
- o The percentage of time on the approach that the pilot spent monitoring the CDI and the directional gyro.

MAP at the time of the sample.

This positional information is represented in Figure 2-1. The matrix in Figure 2-2 shows how the crosstrack error data in Figure 2-1 is organized. The dashed line in the center of Figure 2-2 represents the centerline of the approach course, and the MAP is represented by a zero on the ordinate at the left of the figure. The numbers above the zero on the ordinate represent distances in nautical miles from the MAP.

The three rows, labeled 1, 2, and 3, are called "windows" in this report and are defined by the four distances indicated on the left. For example, Window 1 is between three and five nautical miles from the missed approach point. The seven columns in the matrix are called "zones." The numbers on the abscissa indicate the centerline in the zones and correspond to the numbers on the abscissa of Figure 2-1.

Figure 2-1 shows the crosstrack error performance of the twelve pilots as a function of window and CDI sensitivity. Each data point represents the percentage of time that the pilots spent in that zone for the window and sensitivity indicated. The percentage of time that each pilot spent in each zone was calculated independently for each window. The calculation was made from the crosstrack error data collected on each approach. Summed across zones, the seven percentages represented for a particular sensitivity add up to 100% for each window. Each data point represents data from approximately 24 approaches.

Figure 2-1 also indicates that, as pilots progressed from Window 1 to Window 3, they spent more time in the more central zones, and that the time spent in the more central zones increased with CDI sensitivity. The curves representing the three lower sensitivities are skewed to the right. Pilot performance using the 1/32-mile and 1/64-mile sensitivities is good immediately following the intercept and stays good or improves as the pilot continues along the approach course. Performance at the three lower sensitivities starts out poorly in Window 1 but improves somewhat as the pilots get closer to the MAP.

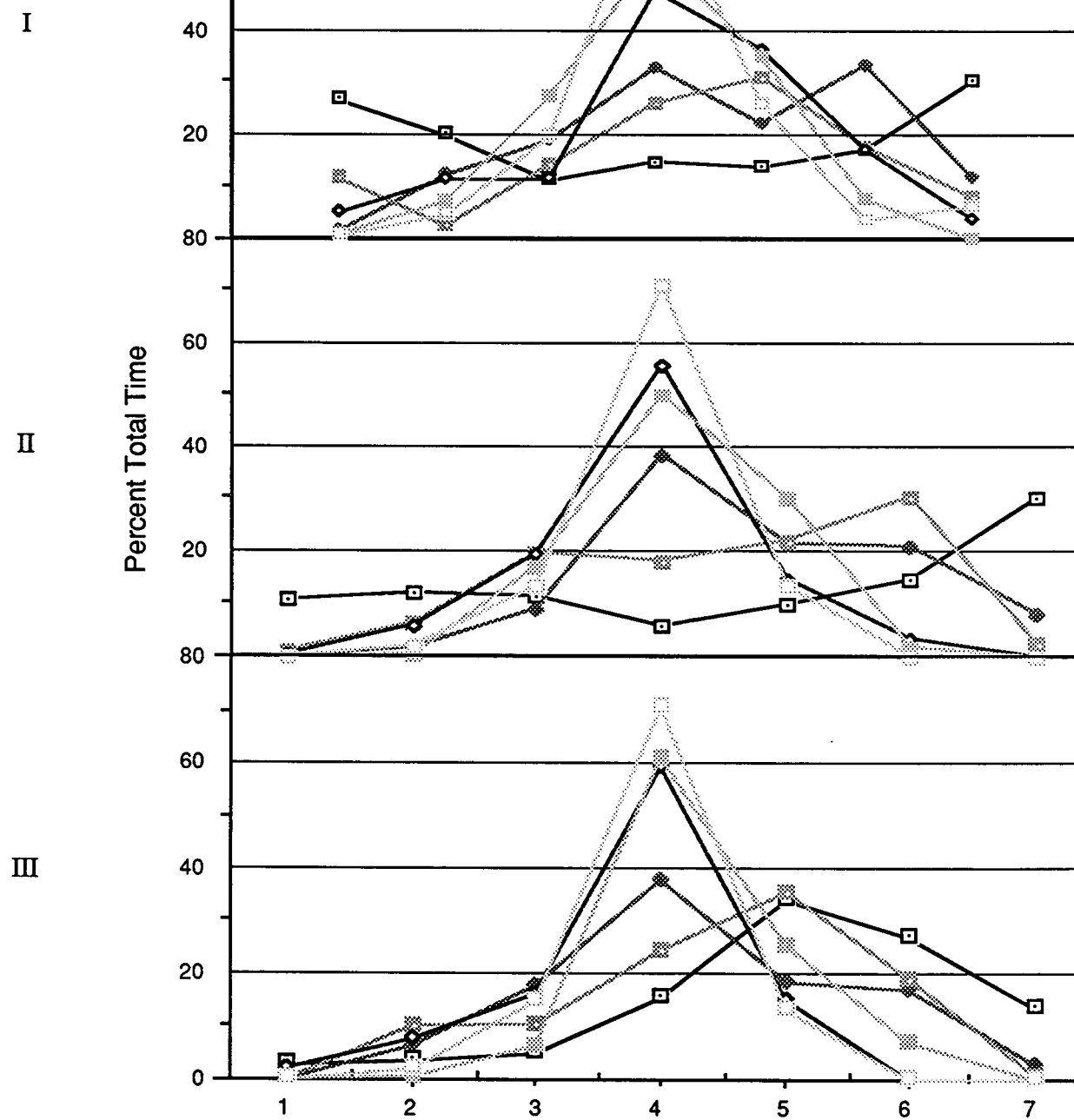


FIGURE 2-1. PERCENTAGE OF TOTAL PILOT TIME SPENT IN EACH OF SEVEN ZONES FOR EACH OF THREE WINDOWS UNDER SIX CONDITIONS OF CDI SENSITIVITY

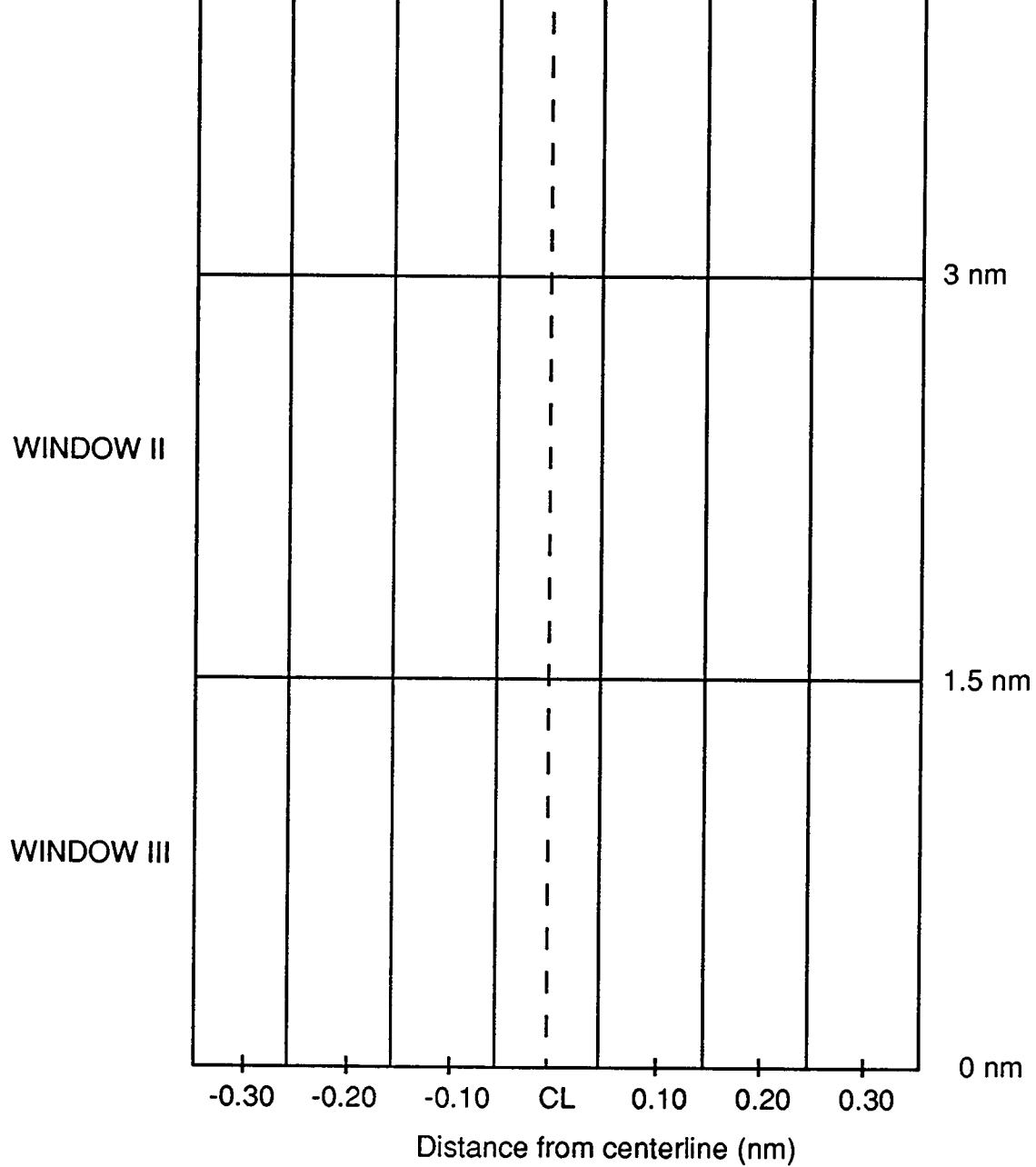


FIGURE 2-2. SCORING MATRIX FOR CROSSTRACK ERROR

values. This conversion changed negative to positive scores (airplane locations to the left of the approach course produced negative scores) and amplified the effects of large errors. The resulting RMS scores appear in Table 2-1 for each sensitivity and the three windows. The score in each cell is the mean of the six pilots' performance.

The statistical significance of the differences among the data was examined with the use of the Statistical Analysis System Procedure for General Linear Models (SAS PROC GLM) computer package for statistical analysis. The effects of window and sensitivity were statistically significant ($F = 10.26$, $df = 2$, $p < 0.01$) and ($F = 152.21$, $df = 1$, $p < 0.01$), respectively. Also significant was the window by sensitivity interaction ($F = 3.57$, $df = 2$, $p < 0.05$).

Table 2-1 illustrates these three effects:

- o The size of the error decreases as the pilot flies from Window 1 to Window 3.
- o The size of the error decreases as sensitivity is increased from $1/2$ to $1/64$ mile per dot.
- o The higher degrees of accuracy that resulted from increases in sensitivity were greater for Windows 1 and 2 than they were for Window 3. This indicates that, with higher sensitivity levels, pilots were quicker in establishing the airplane on the approach course, and they were more accurate in flying the course.

Typical approach path tracks of pilots flying a very sensitive ($1/64$) and a very insensitive ($1/2$) needle appear in Figure 2-3. Notice that pilots have smaller maximum deviations from the centerline and make more centerline crossings when flying with the more sensitive CDIs. Center crossings require a heading change to get back on centerline and thus are a source of increased workload.

CDI Sensitivity

Approach Window	1/2	1/4	1/8	1/16	1/32	1/64	\bar{X}
I	0.26	0.15	0.14	0.09	0.06	0.06	0.13
II	0.23	0.11	0.08	0.05	0.03	0.03	0.09
III	0.14	0.08	0.08	0.05	0.05	0.03	0.08
\bar{X}	0.21	0.11	0.10	0.07	0.05	0.04	0.10

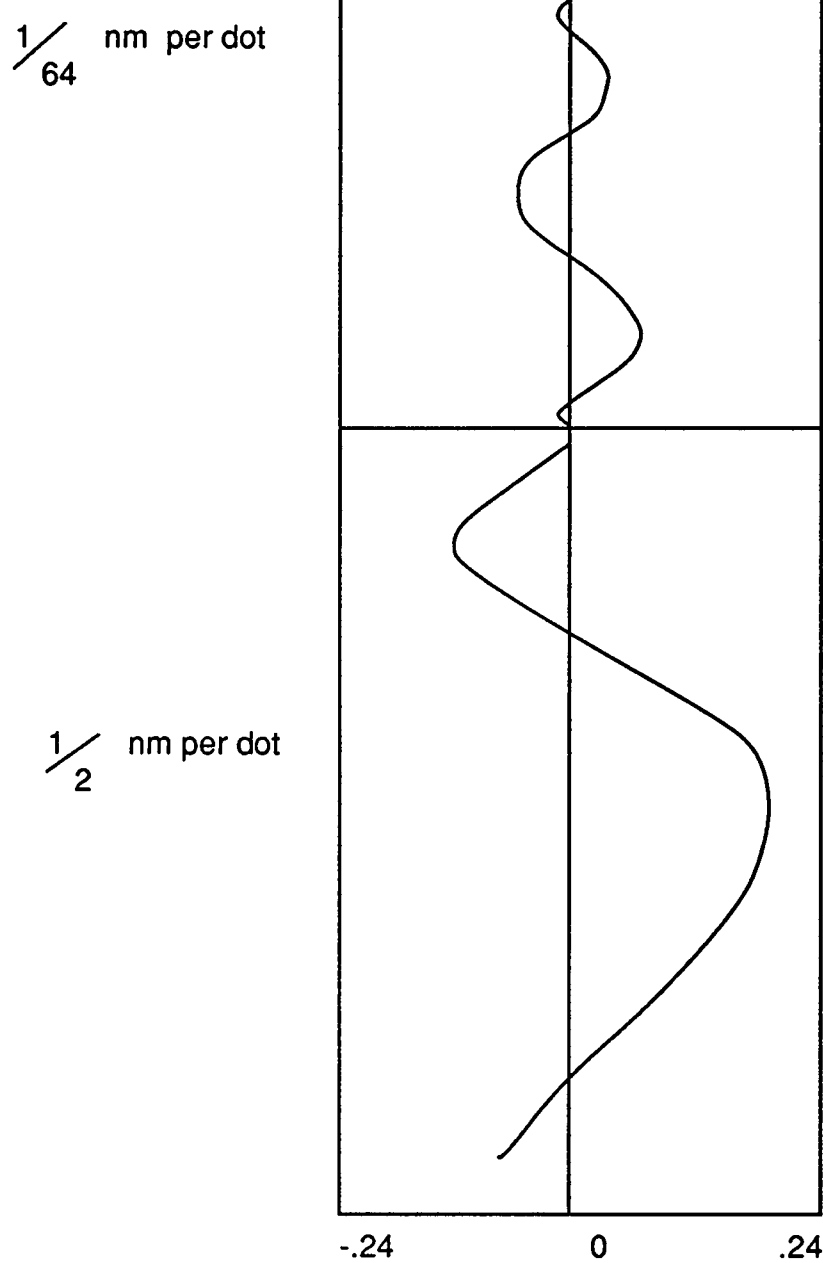


FIGURE 2-3. TYPICAL APPROACH PATH TRACKS FLOWN WITH SENSITIVE (1/64) AND INSENSITIVE (1/2) CDI SETTINGS

runs were calculated. The limits of the horizontal lines illustrating course width represent the mean of the 24 maximums plus two standard deviations from the centerline. The lines are asymmetrical because the calculations were done independently for excursions to each side of the centerline.

This figure is another way of showing the same relations illustrated in Figure 2-1, but it presents the data in a way that is easier to relate to requirements for approach course width. Again, the higher sensitivity levels produce narrower course width requirements. For example, at a distance of 1.5 to 3 miles out from the threshold, the approach course must be 0.63 of a nautical mile to include approximately 95% of all maximum excursions from the centerline if a 1/4-mile CDI sensitivity were used, whereas approximately 1/2 that width (0.32 of a nautical mile) would be required if the 1/16-mile sensitivity level were used.

2.2 SEQUENCE EFFECTS

Several pilots reported that their flying became easier as they became more familiar with the approach procedures; however, toward the end of the seven consecutive approaches they began to tire. Since the test conditions were counterbalanced among pilots, these sequences would not be expected to influence the pattern of test results that we obtained. However, we were curious about the influence of the long test sessions on flying performance.

Figure 2-5 illustrates the RMS crosstrack error scores for each of the six daily test runs averaged across all other test conditions. Performance was worst on the first trial and was best during the second, third, and fourth trials. Performance also tended to tail off after the fourth trial, confirming the pilots' comments about getting tired.

Furthermore, performance was never as good on the odd trials as it was on the following even ones. This seemed to be the result of practice. The pilots had their first experience with a new sensitivity level on the odd trials, and their second experience on the even trials.

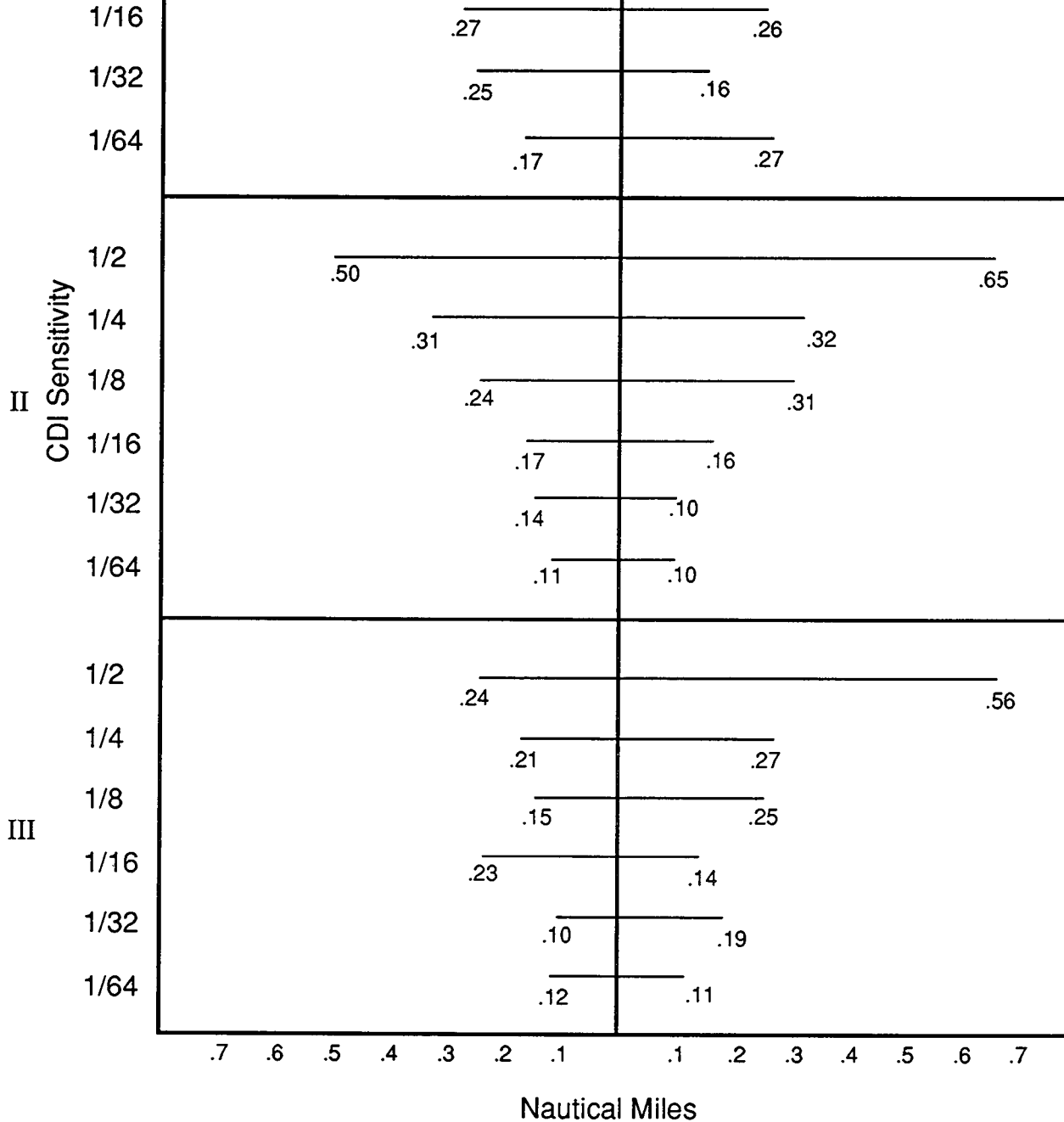
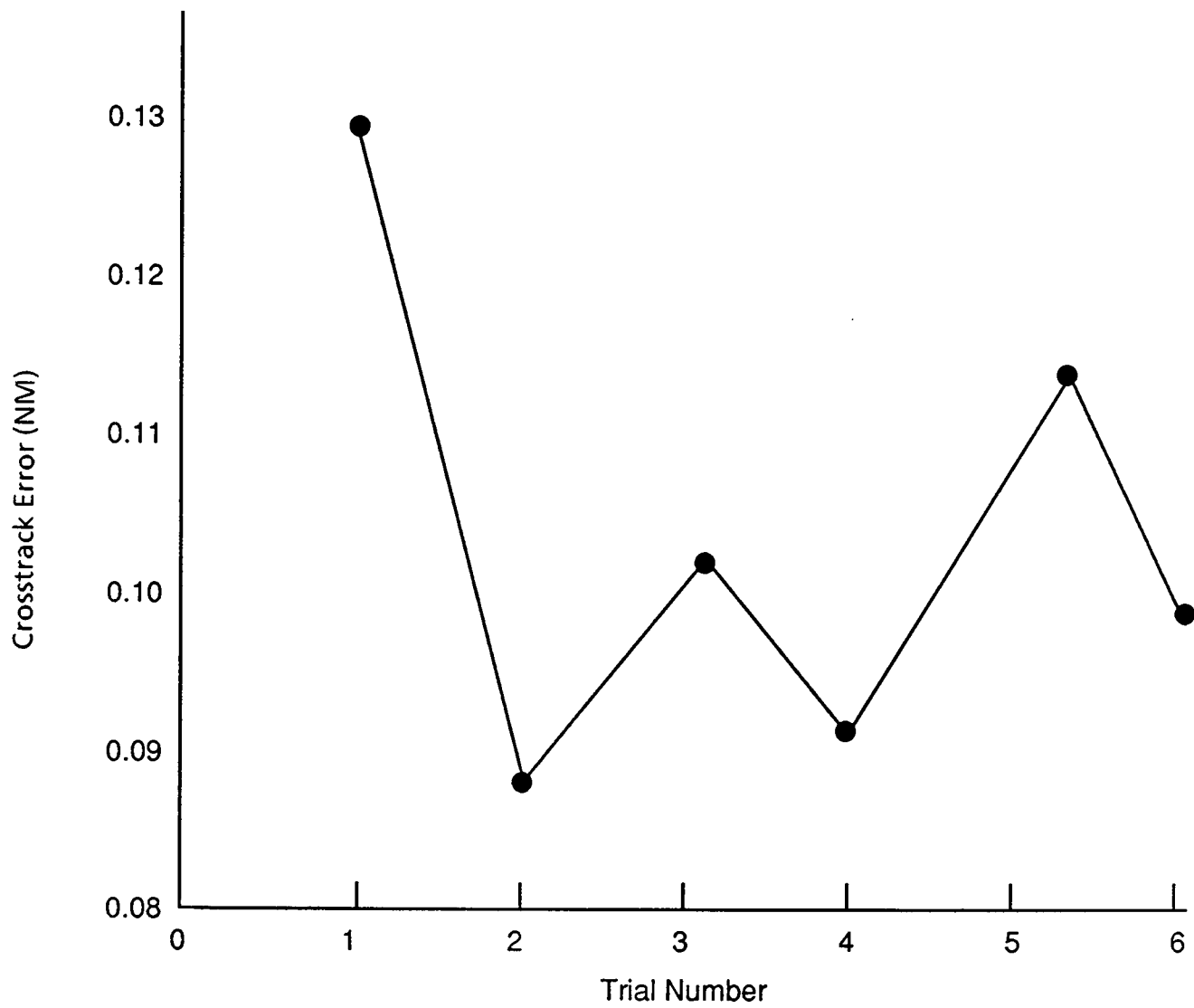


FIGURE 2-4. COURSE WIDTH EXPECTED TO CONTAIN 95 PERCENT OF MAXIMUM DEVIATIONS FROM CENTERLINE AS A FUNCTION OF WINDOW AND CDI SENSITIVITY



Note: Scores are averaged across pilots, test day, and CDI conditions.

FIGURE 2-5. RMS CROSSTRACK ERROR FOR EACH CONSECUTIVE DAILY TEST TRIAL

During the debriefing, each pilot was asked to estimate the percentage of time spent monitoring the CDI and the directional gyro (DG) during each of the three pairs of approaches of the day.

Table 2-2 shows the pilot estimates of time spent monitoring the DG and course deviation (CD) for each of the six sensitivity levels. Each of the twelve averages shown in the body of the table is the mean of approximately twelve estimates.

The table shows three particularly interesting influences of CDI sensitivity on the pilots' reported distribution of attention. At lower sensitivity levels, they spent more than twice as much time watching the DG as they did the CDI. But at the highest levels that relationship was reversed, indicating that the higher levels of sensitivity caused them to "fly the needle" rather than a heading.

Pilots spent more time monitoring the CDI as sensitivity increased. Consequently, they spent less time monitoring the DG and other instruments in the airplane. The biggest jumps in the monitoring time for the CDI were between the 1/4 and 1/8 and the 1/16 and 1/32 sensitivity levels. Data indicates that the ideal CDI sensitivity for instrument approaches is somewhere between 1/4 and 1/32 mile per dot. These shifts of attention are potentially important indicators of pilot workload and should be verified using measures that are more objective than pilot opinion.

2.4 THE COST OF HIGHER APPROACH PRECISION: WORKLOAD

Each pilot made an estimate of his workload during each window of the approach.

Table 2-3 shows the average of pilot workload estimates for each sensitivity level in each window. The number in each cell is the mean of 19 to 24 workload estimates.

Flight Instrument	1/2	1/4	1/8	1/16	1/32	1/64
CDI	15	17	28	28	43	47
Gyro	37	33	31	30	29	21
Total	52	50	59	58	72	68

TABLE 2-3. PILOT ESTIMATES OF WORKLOAD OBTAINED IN THE THREE APPROACH WINDOWS FOR THE SIX LEVELS OF CDI SENSITIVITY

Window	CDI Sensitivity						\bar{X}
	1/2	1/4	1/8	1/16	1/32	1/64	
I	2.3	3.1	3.1	3.8	4.3	5.5	3.7
II	2.5	3.2	3.0	4.0	4.2	5.6	3.8
III	2.5	3.3	3.2	4.1	4.3	5.6	3.8
\bar{X}	2.4	3.2	3.1	3.8	4.3	5.6	3.8

1/4 and 1/8 or 1/16 and 1/32 levels. Thus the pilots thought increases in sensitivity caused increases in workload, but did not think workload varied from window to window.

At the completion of each approach, the safety pilot estimated on a scale of 1 to 7 how hard the pilot appeared to be working during that approach. Table 2-4 shows the average of the safety pilot estimates of pilot effort for each sensitivity level. The value in each cell is the mean of approximately twelve independent estimates. The table indicates that pilot effort was judged to increase with increases in sensitivity. Scheffee's test revealed that the differences between all pairs except 1/4 and 1/8 and 1/16 and 1/32 were statistically significant.

Figure 2-6 shows the relation between pilot workload and crosstrack error. Clearly, increases in CDI sensitivity cause systematic decreases in crosstrack error and an increase in workload.

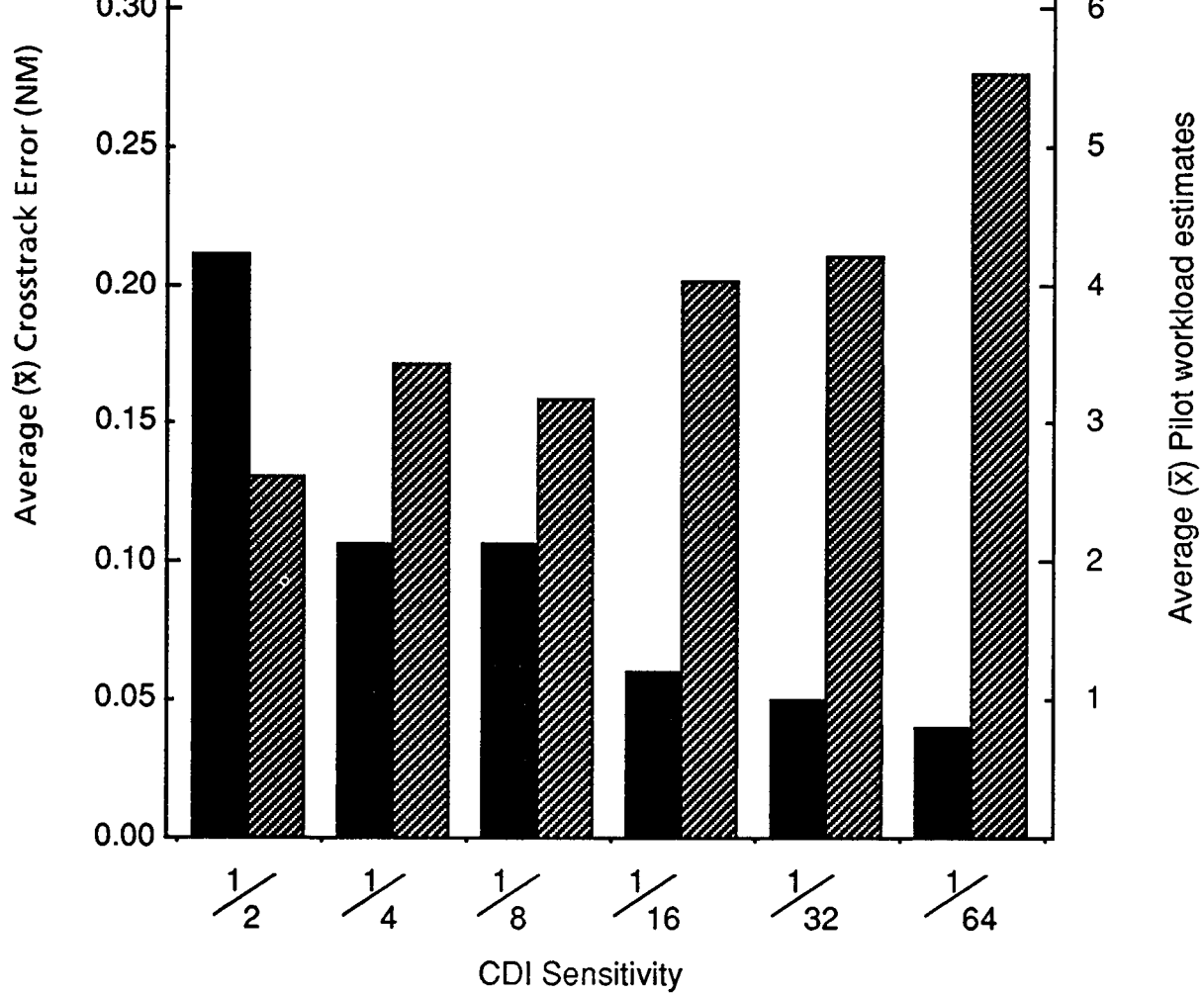
A positive correlation of 0.66 ($p < 0.01$) was produced by a Pearson product moment correlation coefficient calculated between the effort ratings of the safety pilot and the workload estimates of the pilots.

2.5 THE COST OF HIGHER APPROACH PRECISION: FLIGHT SMOOTHNESS

We examined the statistical significance of the influences of CDI sensitivity, pilot, and window on the seven objective performance measures (turn rate and altitude variation, etc.). To do this, we used the SAS PROC GLM computer package for statistical analysis.

The analyses were performed primarily on RMS difference scores of the objective measures. Difference scores were calculated as roughness indicators in handling the airplane. RMS transformations were done to increase the sensitivity of the analysis. Second differences were calculated for altitude as indicators of variation around the normal descent path that was required for the approach.

$1/2$	$1/4$	$1/8$	$1/16$	$1/32$	$1/64$
2.7	3.4	3.0	4.0	3.6	5.1



Note: The results of analysis for differences among pilots are not shown.

FIGURE 2-6. CROSSTRACK ERROR AND PILOT WORKLOAD ESTIMATES FOR THE SIX CDI SENSITIVITY LEVELS

- o Turn rate differences were the least for Window 1.
- o Sensitivity produced significant effects in heading and roll rate variation. In both cases, variation was highest for the higher sensitivity levels, probably because the higher levels were associated with more centerline crossings.
- o No statistically significant window by sensitivity interactions were found.
- o Significant ($p < 0.01$) differences were found among pilots for all six measures.

These results indicate that increases in CDI sensitivity do influence flight smoothness. However, other than as possible indicators of pilot workload, the practical significance of these findings is unclear.

2.6 FLIGHT SMOOTHNESS AS A MEASURE OF WORKLOAD

Table 2-6 shows the results of multiple regression analyses (PROC GLM; Pcorr2) that were conducted. These analyses were conducted between the measures of flight smoothness and the subjective measures (pilot estimates of workload and safety pilots' estimates of pilot effort). The objective measures recorded during each approach are listed in the left column of the table.

Workload and pilot effort are represented as column headings. The cells of the table contain the correlation of the corresponding row and column variables and the level of statistical significance of that correlation. The "Pcorr2" option of PROC GLM was used to partial out the influence of CDI sensitivity on these correlations. This was done to control the fact that both the pilot and the safety pilot knew the CDI conditions under which they were flying during each approach. That knowledge might have influenced their workload and effort estimates.

Measure	1	2	3	4	5	6	7	8	9
Ground speed/d (kts)	* 0.4	0.2	0.2	0.3	0.2	0.3	0.4	0.3	0.3
Altitude/2d (ft)	* 56.0	55.3	47.6	47.9	53.7	44.9	64.6	49.5	58.7
Heading/d (deg)	1.8	1.8	1.8	* 1.7	1.6	1.9	1.8	1.9	2.1
Pitch/d (deg)	1.2	1.3	1.4	1.4	1.3	1.2	1.5	1.0	1.6
Roll/d (deg)	2.6	2.6	2.7	* 2.4	2.2	2.6	2.5	3.0	3.1
Turn rate/d (deg/sec)	* 2.2	2.4	2.6	2.4	2.3	2.5	2.2	2.4	2.5

* p < 0.01

Measure	Effort	Workload
Cross Track Error	+ 0.06	* + 0.19
Ground Speed/d	+ 0.11	+ 0.10
Altitude/2d	+ 0.02	+ 0.11
Heading/d	* + 0.28	* + 0.15
Pitch/d	* + 0.14	-0.04
Roll/d	* + 0.29	+ 0.06
Turn rate/d	* + 0.21	+ 0.06

*p < 0.01

It is generally accepted that the best estimate of pilot workload is the pilot's own report. This is believed true even if (as is generally believed) the pilot's memory limits, ego, and expectations may influence such estimates. It is possible, however, that the safety pilot, with less ego involvement and more time to attend to details, could provide more useful estimates of pilot workload.

Heading, pitch, roll, and turn rate differences were associated significantly with the safety pilots' estimates of pilot effort. Only crosstrack error and heading differences are significantly associated with pilot estimates of workload. This indicates that - to the extent that workload is reflected in how the pilot handles the airplane - an observer may be a better judge of pilot workload than the pilot himself.

2.7 CONCLUSION

Tables 2-1, 2-2, 2-3, 2-4, and 2-5 indicate that the increase in CDI sensitivity resulted in more accurate flying of the final approach course. This accuracy was accomplished at the cost of a narrowing of visual scan in the cockpit, increased pilot workload, and some decrease in flight smoothness.

Further, observations by a cockpit observer of pilot behavior during instrument approaches appeared to be a useful source of information on pilot workload.

- o Pilot estimates of workload, instrument scan, and CDI "flyability" indicated that the workload increased and the extent of instrument scan decreased with increases in CDI sensitivity.
- o CDI sensitivity did cause a significant change in the quality of the pilot's handling of the airplane. Pilot and safety pilot estimates of workload were significantly correlated. However, the estimates of the safety pilot appeared more highly correlated with objective measures of flight quality, such as variations in pitch, roll, and turn rate, than were the pilot estimates.

Our study indicates that for certain instrument approach conditions, a more sensitive CDI than the standard currently used may be advantageous. For these airports, which cannot have wide approach courses due to terrain, a CDI sensitivity of 1 1/4 mile off course for full-scale deflection is most often used. This sensitivity is also recommended by the Radio Technical Commission for Aeronautics (RTCA) for LORAN-C instrument approaches. However, we found that using a more sensitive needle, which deflected to full scale when only one-quarter of this distance off course (1,900 ft.), would decrease crosstrack error by 40% to 30%.

Crosstrack error accounts for a major proportion of system error budget used by procedure design specialists for designing LORAN-C instrument approaches. Reducing the value of the crosstrack error (flight technical error) component of this budget could narrow the path that needs to be cleared for LORAN-C approaches, thus making such approaches possible in locations where currently they are not.

The problem with an increase in CDI sensitivity is uncertainty about the workload that may accompany it. Our results indicate that although a measurable increase in workload is likely with such an increase, large changes in pilot control of the aircraft would not occur.

- o Much time and effort have been spent on developing procedures for structuring pilot judgment for better estimating pilot workload. Similar efforts concerning the judgment of an observer in the right seat should be taken.
- o Research is needed on the impact of cockpit workload on pilot visual scan. Changes in visual scan could provide an objective measure of workload that has both operational and face validity. Techniques should be developed for measuring the pilot's visual scan in the cockpit. The more difficult the task is, the more visual scan is reduced. This phenomenon has been demonstrated in the laboratory and in automobile tests on the highways. However, such demonstrations use equipment and data analysis procedures that are impractical for cockpit use.
- o Logically, workload would influence how the pilot handles his aircraft, and we have some data to support this notion. This relationship should be researched directly by examining the influence of workload on pilots' use of the yoke.

A-1/A-2

CD	Course Deviation
CDI	Course Deviation Indicator
CTAF	Common Traffic Advisory Frequency
D	
DG	Directional Gyro
E	
F	
FAF	Final Approach Fix
FTE	Flight Technical Error
G	
H	
I	
IAF	Initial Approach Fix
IFR	Instrument Flight Rule
ILS	Instrument Landing System
J	
K	
L	
LORAN	Long-range Navigation
M	
N	
NM	Nautical Mile
O	
P	
Q	
R	
RMS	Root Mean Square
RTCA	Radio Technical Commission for Aeronautics

